NAVAL HEALTH RESEARCH CENTER

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FIREFIGHTING ENSEMBLE INCREASES HEAT

EXPOSURE STAY TIME

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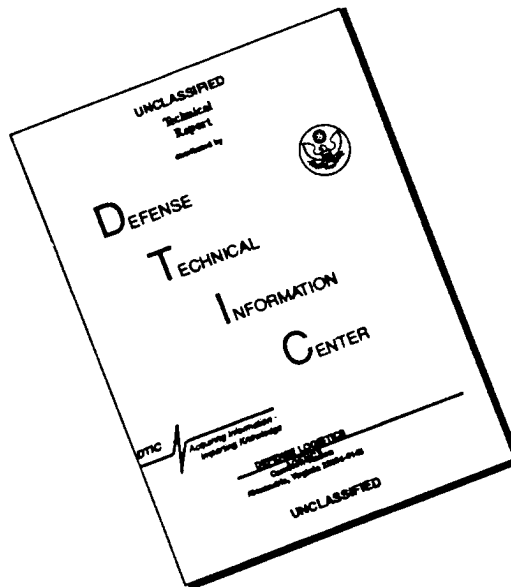
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CORE-CONTROL™ COOLING SYSTEM WORN UNDER FIREFIGHTING ENSEMBLE INCREASES HEAT EXPOSURE STAY TIME

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SUMMARY

Problem.

Physical activity in the single-piece U.S. Navy firefighting ensemble and exposure to high environmental temperatures leads to progressive elevations in body temperature and heart rate. Studies of men working in warm environments indicate that heat strain can be reduced when subjects wear a water-circulating tube suit (WCTS) connected to a high capacity heat-exchange unit (HEU). Unfortunately, such systems are not practical for shipboard firefighting because the HEU must be tethered to the tube suit. An alternative to a tethered HEU is a portable HEU carried by the individual. However, the effectiveness of WCTS using portable HEU systems to minimize heat strain in men dressed in firefighting protective clothing is unknown.

Objective.

The primary objective of this study was to investigate the effectiveness of a WCTS and portable HEU, the Core-Control™ System (CCS), in reducing heat strain and extending stay time in men dressed in the U.S. Navy firefighting ensemble (FFE) and breathing on an A-4 oxygen breathing apparatus (OBA) while resting and exercising in a hot/humid environment.

Approach.

Laboratory tests were conducted in an environmental chamber. The ambient conditions were $48 \pm 0.5°C$. The relative humidity (rh) equalled 50%. Male volunteers (n = 7) served as subjects. All subjects participated in two randomly ordered counterbalanced trials: 1) no cool suit, control (CON); and 2) CCS. CCS (MSA, Inc., Pittsburgh, PA) consisted of a network of tubing sewed into a two-piece cotton pants and shirt undergarment. The HEU contained a 2 L plaster bottle filled with ice. Water was pumped through the tubing network of the suit by a battery-operated pump, and passed over the ice in the container, thereby promoting heat exchange. CCS was worn under a cotton T-shirt and dungarees. During each heat exposure trial, the subject attempted to complete as many cycles as possible of 30 min seated rest and 30 min walking on a motorized treadmill (1.16 m·s^{-1}/2.5 mph, 0% grade). Heat-exposure stay time was established when subjects desired to terminate heat exposure or after attainment of established medical criteria. Throughout each trial, subjects were monitored continuously for heart rate (HR),

rectal (T_{re}), chest (T_{ch}), upper arm (T_{ua}), thigh (T_{th}), and calf (T_{ca}) temperatures. Measures of oxygen uptake (VO_2) and carbon dioxide production (VCO_2) for calculation of energy expenditure in Watts (W), cardiac output (Q_c), stroke volume (SV), and ratings of perceived exertion (RPE) and thermal sensation (TS) were recorded during each rest and exercise period.

Results.

Heat-exposure stay time for CCS (76.6 ± 10.9 min) was significantly longer (p < .05) than CON (49.0 ± 6.6 min). Energy expenditure averaged 85 ± 19 W during rest and 400 ± 43 W during exercise with differences between CCS and CON nonsignificant. HR rose slowly during the first rest period and rapidly during the first exercise period for both CCS and CON. HR response for CCS was significantly lower than CON starting midway through the first rest and continuing during the first exercise period until termination from heat exposure. For CCS, HR declined during the second rest period, then gradually increased until termination of the test.

Differences in T_{re} between CCS and CON were nonsignificant during the first rest period, while skin temperatures for CCS were significantly lower. During the first exercise period, the rate of increase in T_{re} for CON exceeded the increase for CCS. During this time, T_{ch}, T_{ua}, T_{th}, and T_{ca} for CCS remained significantly below CON, but rose rapidly throughout exercise. At termination from heat exposure, differences in peak T_{re} and skin temperatures between CCS and CON were nonsignificant.

Conclusions.

CCS significantly increased stay time during rest and exercise in a hot/humid environment (48°C/50% rh). CCS was also associated with overall slower rates of increase in HR and body temperatures. Despite reduction in heat strain, CCS does not appear to be practical for shipboard firefighting activities. Positioning the portable HEU on one side of the torso outside of the FFE encumbered movement and contributed to discomfort and general fatigue.

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INTRODUCTION

Shipboard firefighting can produce rapid and large increases in heart rate (HR) and body temperatures (Bennett et al., 1993a). The extremely high air temperatures and presence of steam indicates the need to identify and investigate different countermeasures to heat strain for use by damage control personnel during training and actual shipboard operations. In previous studies, Bennett et al. (1993b), Hagan et al. (1994) and Ramirez et al. (1995) reported that torso cool vests reduced heat strain in males wearing the U.S. Navy single-piece firefighting ensemble (FFE) and exercising in warm/humid and hot/humid environments. However, the heat-strain reduction capacity provided by torso cool vests is limited.

The findings from several studies suggest that heat strain reduction is best accomplished using a water-circulating tube suit (WCTS) system connected to a high-cooling capacity heat-exchange unit (HEU) (Nunneley, 1970; Shvartz, 1972). During steady-state exercise, the cooling required to suppress sweating and maintain thermal balance is approximately 80% of energy expenditure (Webb & Annis, 1968). However, 580 Watts (W) of energy expenditure appears to be the upper limit of heat production compatible with the achievement of thermal balance using a WCTS and tethered HEU system (Waligora & Michel, 1968). At this level, skin temperatures become uncomfortably cool and heat transfer from the body core to skin limited by cutaneous vasoconstriction. Webbon et al. (1981) also reported that leg blood flow in working muscles is decreased by whole-body cooling using a WCTS. During heat exposure in air temperatures up to 50°C, Shvartz and Benor (1971) reported significant reduction in heat strain and maintenance of thermal balance by a WCTS and tethered HEU in individuals wearing vapor-impermeable clothing and walking on a treadmill at 275 W of energy expenditure. However, the HEU had to produce 907 W of cooling to achieve individual thermal balance. Thus, tethered HEU systems may not be feasible for shipboard firefighting because of the need for the HEU to possess a large cooling capacity and for the HEU to be tethered to the WCTS. Such a system would surely reduce personnel mobility and increase firefighting response time. However, another approach is the use of a portable HEU which provides either a fixed cooling capacity or a set rate of heat exchange.

Cadarette et al. (1992) and Pimental et al. (1988) evaluated commercial water- and liquid-circulating torso vest systems with cooling capacities ranging from 220 to 240 W, and reported reductions in heat strain during exercise in a hot environment while wearing heavy insulated clothing. Cadarette et al. (1992) considered these systems inadequate for prolonged physical activity but suggested that they might be useful for short-term physical activity. However, evidence exists showing that a whole-body WCTS and portable HEU system is superior to active- and passive-cooling torso vest systems.

Bernard et al. (1992) compared the heat-strain reduction effectiveness of the whole-body Core-Control™ System (CCS) with portable HEU against a gel-pack torso cool vest equivalent to the vest evaluated by Bennett et al. (1993b), and a liquid-circulating cool vest similar to one evaluated by Caradette et al. (1992). In the Bernard et al. (1992) study, the environmental conditions were described as high (38°C dry bulb and 60% relative humidity). The findings showed that use of CCS reduced core temperature and heart rate and allowed subjects to exercise for 2 hrs compared to 30 to 62 min for the cool vest and 43 to 49 min for the liquid cooling vest. While these findings suggest that CCS can reduce heat strain, the magnitude of this reduction in men wearing heavy and highly insulated protective clothing and resting and exercising in extremely hot and very humid conditions has not been established. Therefore, the purpose of this study was to investigate the effectiveness of CCS using a portable HEU in minimizing heat strain and extending stay time in men dressed in the U.S. Navy FFE and oxygen breathing apparatus (OBA) while resting and exercising in a hot/humid environment.

METHODS

Subjects.

Seven males, experienced in U.S. Navy firefighting procedures and equipment, served as subjects (24 ± 5 yrs; 174 ± 7 cm; 72.3 ± 7.3 kg; 1.86 ± 0.1 m2; 13.4 ± 4.5 % body fat; maximal oxygen uptake capacity [VO$_2$max] 41.4 ± 4.3 ml·kg^{-1}·min^{-1}). Each subject gave informed consent prior to participation in the study.

Medical Screening.

Before the heat exposure trials, all subjects underwent medical screening which included a medical history questionnaire, body composition assessment, and resting electrocardiogram (ECG). Body surface area, as square meters (m^2), was calculated according to the height and weight regression equation of DuBois (Carpenter, 1964). A U.S. Navy regression equation was used to calculate percent body fat using height and circumference measures at the neck and abdominal regions (Hodgdon & Beckett, 1984).

All subjects completed an incremental treadmill exercise test to volitional exhaustion (Bruce et al., 1973). This test was conducted to determine the capacity of each subject to manage the combined stressors of exercise and heat exposure. In this test, skin surface ECG electrodes were placed on each subject's chest according to the Mason-Liker configuration. Two electrodes were placed on the upper chest near the shoulders and two others on the waist towards the sides of the body. Six electrodes were also placed on the chest around the lower border of the left pectoralis major muscle. Resting ECG tracings and measures of HR and blood pressure were taken in supine, seated, and standing positions. Peak HR was recorded as the highest HR obtained during the graded treadmill exercise. Throughout walking recovery, the subject's HR and blood pressure were monitored until return to resting values. Pulmonary oxygen uptake (VO_2) and carbon dioxide production (VCO_2) were measured continuously during exercise using a breath-by-breath open circuit system (MedGraphics, Inc., St. Paul MN).

Experimental Procedures.

The previous night and the morning of the heat exposure test, subjects were instructed to drink 1 L of fluid (noncaffeine beverages) to ensure normal body hydration. Euhydration was accepted if urine collected prior to each heat-exposure trial possessed a specific gravity < 1.030.

The ambient conditions were 48 ± 0.5°C (118 ± 0.9°F) dry bulb (DB), 37 ± 0.1°C (99 ± 0.2°F) wet bulb (WB), and 41 ± 0.2°C (104 ± 0.4°F) wet bulb globe temperature (WBGT). The relative humidity (rh) was 50%. During the heat-exposure trials, each subject attempted to

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complete as many cycles as possible of 30 min seated rest and 30 min walking on a motorized treadmill at 1.16 m·s⁻¹(2.5 mph) and 0% grade.

All subjects participated in two randomly ordered counterbalanced trials. The trials were: 1) no cool suit (CON), and 2) CCS. During the CCS trials, subjects carried a total weight of 24 kg (53 lb) (FFE, OBA, and CCS). During the CON trials, subjects carried a total of 18 kg (40 lb) (FFE and OBA).

During each test, subjects wore the U.S. Navy dungaree uniform as the undergarment. This consisted of cotton T-shirt, long sleeve cotton shirt, denim pants, socks, and boondocker boots. The protective overgarment consisted of the standard U.S. Navy FFE. This ensemble included flash hood, hard helmet with plastic visor, gloves, single-piece fire-retardant suit, and an OBA. In the CCS trial, the tube suit was worn under dungarees and FFE.

The CCS (Mine Safety Appliances, Inc., Pittsburgh, PA) consisted of a hood for the head and a two-piece undergarment made of 100% Nomex aramid fabric (Exotemp, Inc., Pembroke, Ontario, Canada). The Nomex garment was worn under dungarees against the skin. Sewn into the two-piece Nomex garment was approximately 76 m (250 ft) of plastic tubing, spaced about 2 cm apart. The tubing was connected to a 2 L plastic container filled solid with ice. Prior to each test, the container was filled with tap water and placed in the refrigerator freezer to freeze. The container was held in a case. Connected to the ice container was a battery-operated pump which when activated, pumped water through the tubing network of the undergarments and over the ice in the plastic container, thereby allowing the ice container to serve as a HEU. The complete HEU (Nomex undergarments, ice container, pump, battery, case, and strap) weighted about 6 kg (13 lb). The HEU was worn on the outside of the FFE. During walking, the HEU was strapped over the shoulder and placed over the right hip. The HEU was activated at the start of the first rest period inside the environmental chamber.

Prior to each heat exposure test, subjects inserted a rectal thermistor to a depth of 20 cm in the rectum. Skin temperature thermistors were placed over the right deltoid, upper right

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pectoralis, midlateral vastus lateralis, and midlateral gastrocnemius muscles. Three ECG electrodes were placed on the chest to monitor HR. Rectal (T_{re}), right chest (T_{cb}), right upper arm (T_{ua}), right thigh (T_{th}), and right calf (T_{ca}) temperatures, and HR were recorded at 1-min intervals by a portable data logger (Science/Electronics, Miamisburg, OH 45342). The data logger was worn outside the FFE. HR was also recorded by a Polar Heartwatch (Polar, USA, Inc., Stamford, CT).

Throughout each test, subjects were asked to rate their perception of physical exertion and thermal sensation at 15 min intervals. Subjects became familiar with the scales during pretest briefings. Ratings of perceived exertion (RPE) were determined from the Borg 15-point scale (Borg, 1982), while ratings of thermal sensation (TS) were determined using an 8-point scale (Young, 1987). TS included an overall body rating as well as ratings from five local body areas (head, neck, chest, arms, and legs).

Pulmonary VO_2 and VCO_2, and cardiac output (Q_c) were measured once in the middle of each rest and exercise period. The hard helmet and OBA were removed and the subject's pulmonary gas exchange was measured for 2 min using a metabolic measurement system (Med-Graphics, Inc., St. Paul, MN). Energy expenditure (Watts [W]) was calculated from VO_2 and VCO_2. Q_c was determined by a CO_2 rebreathing method (Jones & Campbell, 1982). The rebreathing gas contained approximately 12% carbon dioxide and 88% oxygen. HR was measured concurrently to determine stroke volume (SV) which was calculated by dividing Q_c by HR. Immediately after measurement of energy expenditure and Q_c, subjects were allowed to drink as much water as desired. After drinking, subjects put back on the OBA and hard helmet.

Total-body sweat loss, in liters, was calculated as the difference between pretest and posttest nude body weight with the posttest weight corrected for water intake and urine output. Fluid balance in liters (L) was calculated as the sum of water intake, urine output, and sweat loss.

Removal of subjects from heat exposure and the recording of heat exposure stay time were based on the following criteria: 1) attainment of 39.5°C T_{re} during exercise, or 39.2°C T_{re}

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during rest; 2) rise in T_{re} of greater than 0.5°C per 5 min of exposure duration, excluding the initial 10 min of exercise; 3) HR greater than 80% and 90% of maximum for a 5-min period during rest and exercise, respectively; 4) absence of sweating or presence of chills, nausea, weakness, or dizziness; or 5) subject desire to terminate heat exposure.

Statistical Analysis.

Data were statistically analyzed by t-test and two-way analysis of variance with repeated measures. In the presence of a significant omnibus F-ratio, comparison of means was conducted using the Newman-Keuls post hoc test. Significance is reported at $p < .05$.

RESULTS

Stay Time.

Heat-exposure stay time for CCS (76.6 ± 10.9 min) was significantly ($p < .05$) longer than CON (49.0 ± 6.6 min). While all CON subjects finished the first rest period, no CON subject finished the first exercise period. This is in contrast to all CCS subjects who finished both rest and exercise periods. During a second rest period, six CCS subjects withdrew from heat exposure, while the last CCS subject withdrew during the early minutes of a second exercise period.

Stay time based on attaining HR criteria, occurred in four of seven CON subjects compared to two of seven CCS subjects (Table 1). Stay time based on physical symptoms of general fatigue, headache, and feeling very "hot" accounted for 8 of 14 terminations from heat exposure for both CCS and CON.

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Table 1.   **Frequency of Stay Times Associated with Criteria Categories.**

Criteria	CON	CCS
high rest/exercise HR	4	2
$T_{re} \geq 39.5°C$	1	1
General fatigue	0	3
Headache	0	0
Feel very "hot"	2	1

Energy Expenditure, Cardiovascular Responses, and Fluid Balance.

Differences in energy expenditure between CCS and CON were nonsignificant and averaged 85 ± 19 W during the first rest period and 400 ± 43 W during the first exercise period. Analysis of variance for HR revealed significant time and trial effects as well as a significant time by trial interaction. HR increased significantly through the first 40 minutes of heat exposure for both CON and CCS (Fig. 1). Starting midway through the first rest period, HR became significantly less for CCS compared to CON. However, difference in peak HR between CON obtained at the end of heat exposure and CCS obtained at the end of the first exercise period were nonsignificant.

Q_c and SV were significantly (p < 0.5) higher during exercise (13.1 ± 2.2 L·min⁻¹ and 86 ± 16 ml·bt⁻¹) compared to rest (5.0 ± 1.2 L·min⁻¹ and 60 ± 14 ml·bt⁻¹), but differences between CON and CCS were nonsignificant. Differences in total sweat loss between CCS (600 ± 430 ml) and CON (519 ± 316 ml) were also nonsignificant, as were differences in fluid balance between CCS (-0.19 ± 0.57 ml) and CON (-0.14 ± 0.38 ml).
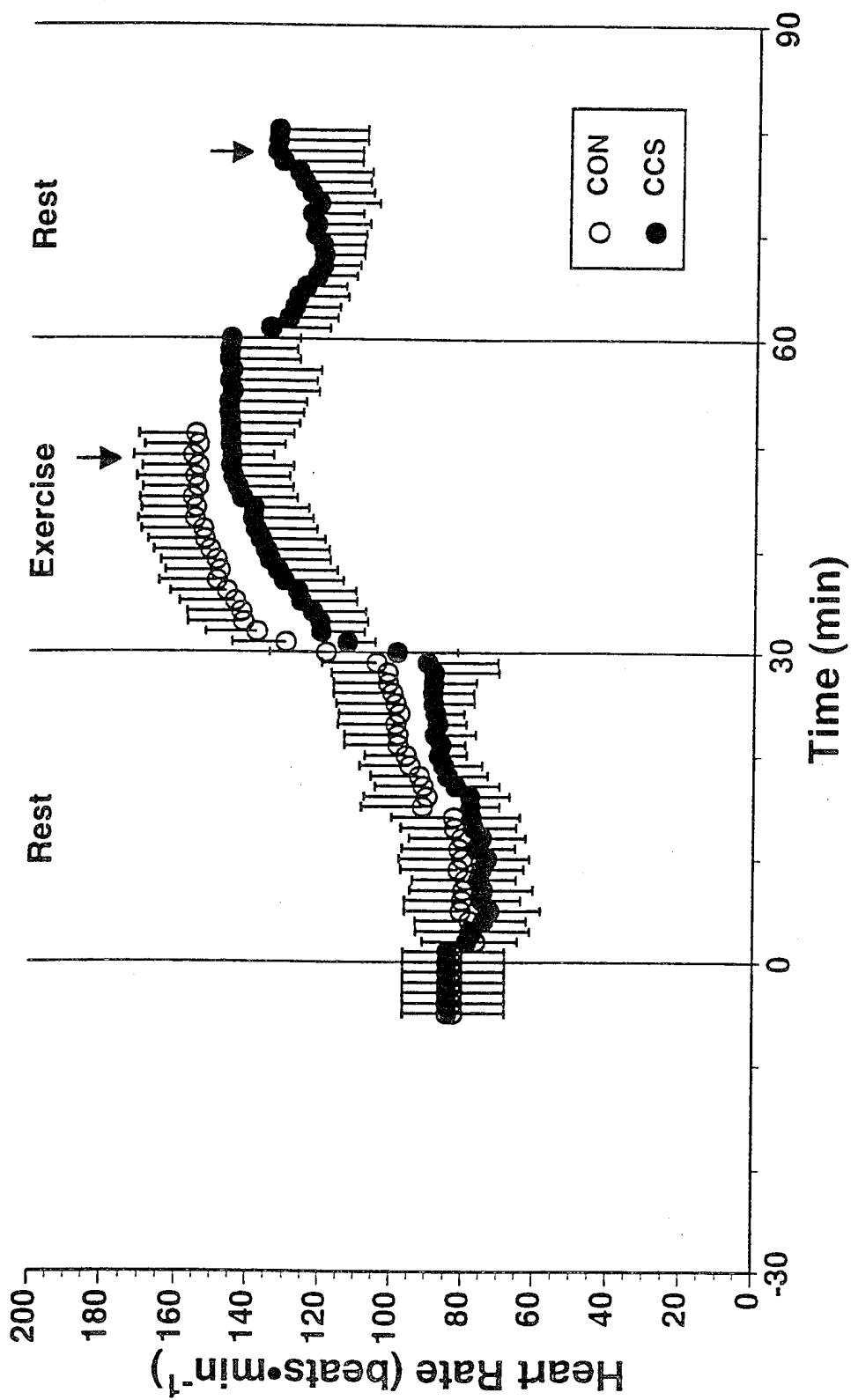
Figure 1. Heart rate responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.

Body Temperatures.

Analysis of the main effects of time to minute 40 of heat exposure and trial (CON vs. CCS), and the interaction of time and trial on body temperatures are shown in Table 2.

**Table 2.   Analysis of variance to minute 40 of heat exposure for body temperatures.**

Variable	Time	Trial	Time x Trial
T_{re}	n.s.	$p = .0001$	$p < .035$
T_{ch}	$p < .0003$	$p < .0024$	$p < .0001$
T_{ua}	$p < .0004$	$p < .0033$	$p < .0001$
T_{th}	$p < .05$	$p < .0001$	$p < .0001$
T_{ca}	$p < .0003$	$p < .0001$	$p < .0001$

During the first rest period, T_{re} increased slowly and similarly for CCS and CON (Fig. 2). However, differences in T_{re} between CCS and CON were nonsignificant. During this period, T_{ch} (Fig. 3), T_{ua} (Fig. 4), T_{th} (Fig. 5), and T_{ca} (Fig. 6) increased rapidly for CON, while the same skin temperatures for CCS either decreased (T_{ch}, T_{ua}, T_{ca}) or increased slightly (T_{th}). At the end of the first rest period, all skin temperatures for CCS were lower ($p < .05$) for CCS (Table 3).

Table 3.   Body temperatures for CON and CCS at the end of the first rest period.

	T_{re} (° C)	T_{ch} (° C)	T_{ua} (° C)	T_{th} (° C)	T_{ca} (° C)
CON	37.2 ± 0.5	$37.7 \pm 0.5^*$	$37.8 \pm 0.5^*$	$37.2 \pm 0.9^*$	$37.2 \pm 0.2^*$
CCS	37.2 ± 0.3	34.1 ± 1.7	35.6 ± 1.2	34.9 ± 1.4	34.3 ± 0.5

*CON values significantly higher ($p < .05$) than CCS.**

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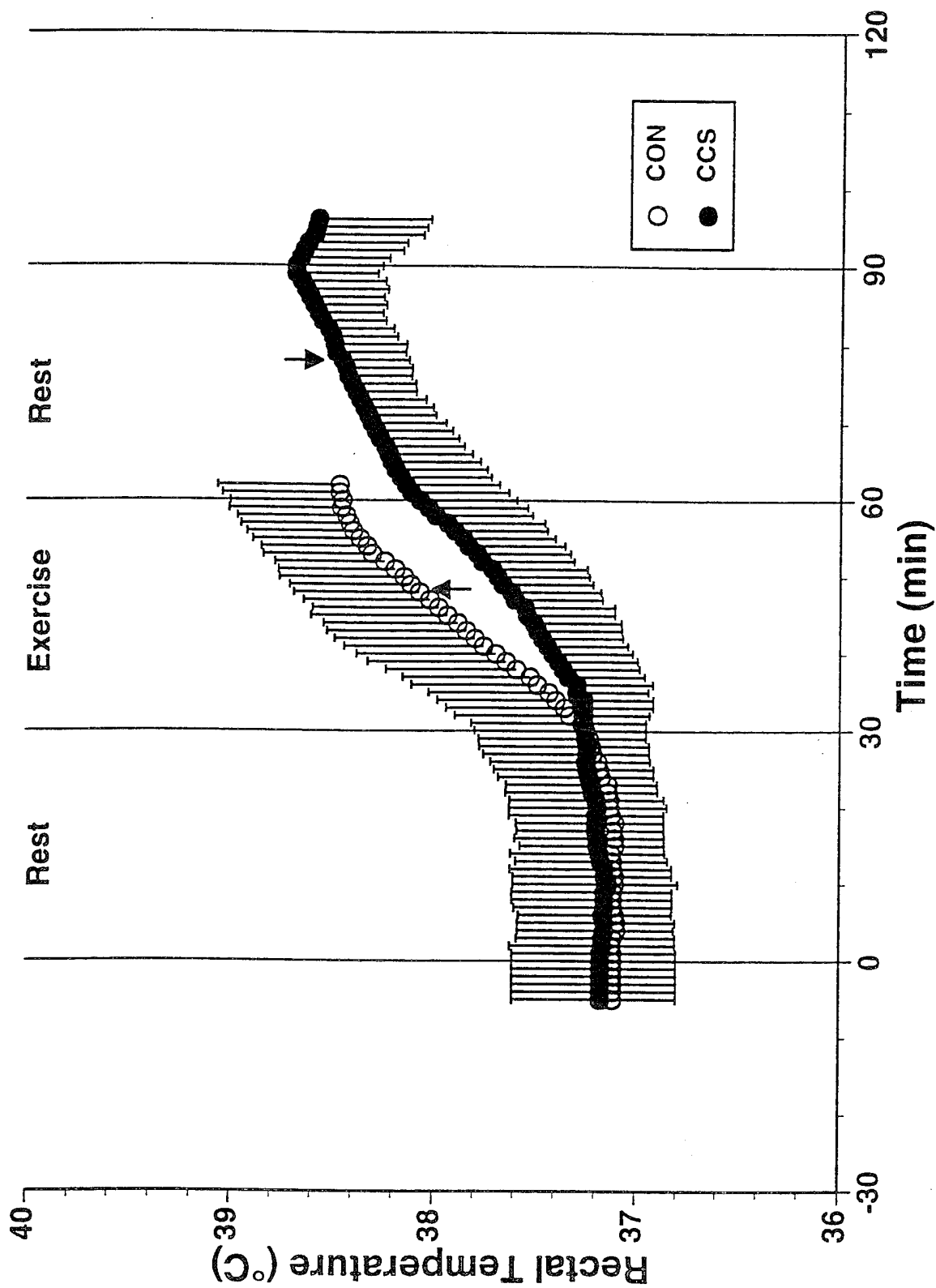
Figure 2. Rectal temperature responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.
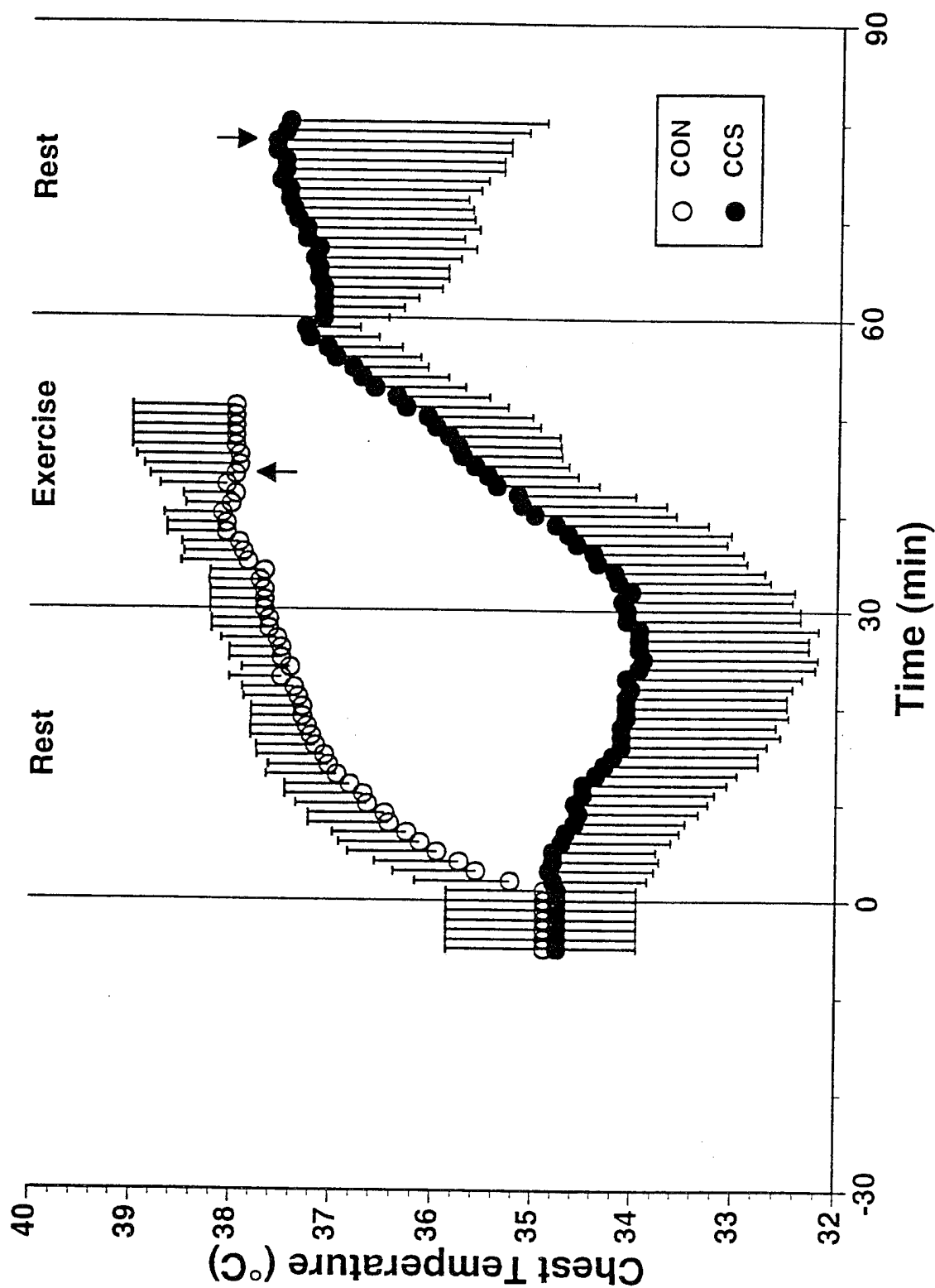
11A

Figure 3. Chest temperature responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.
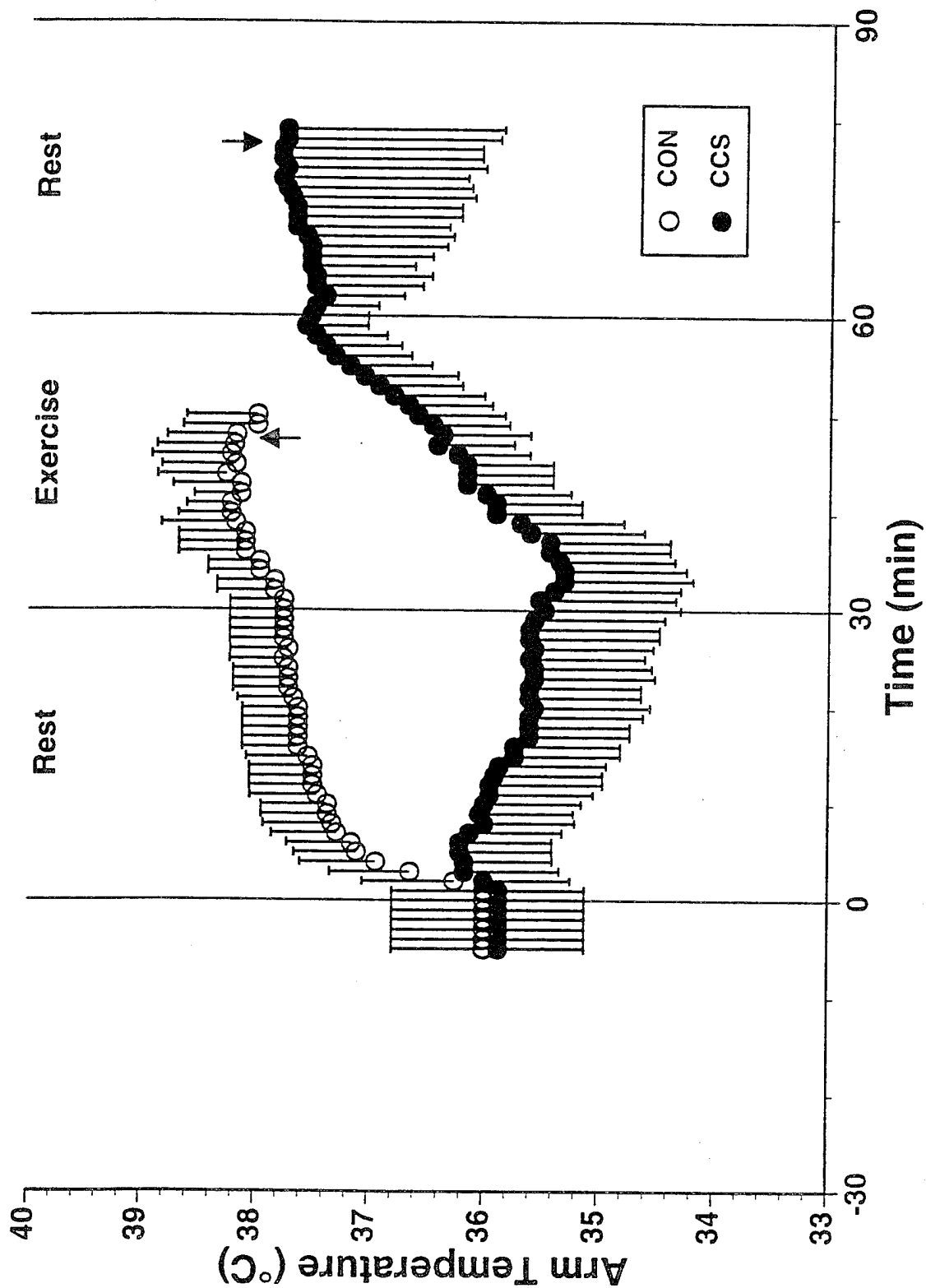
Figure 4. Arm temperature responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.
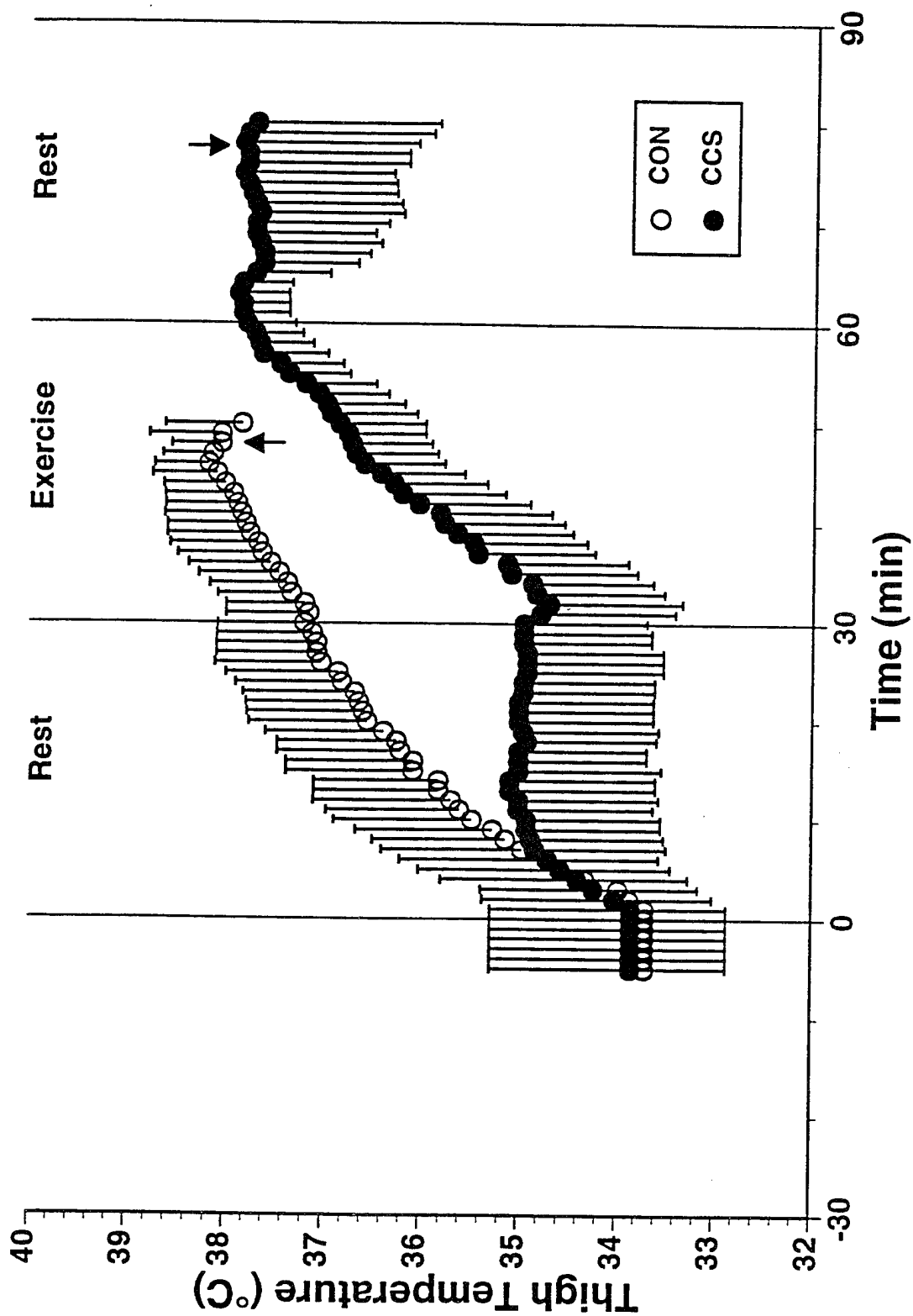
Figure 5. Thigh temperature responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.
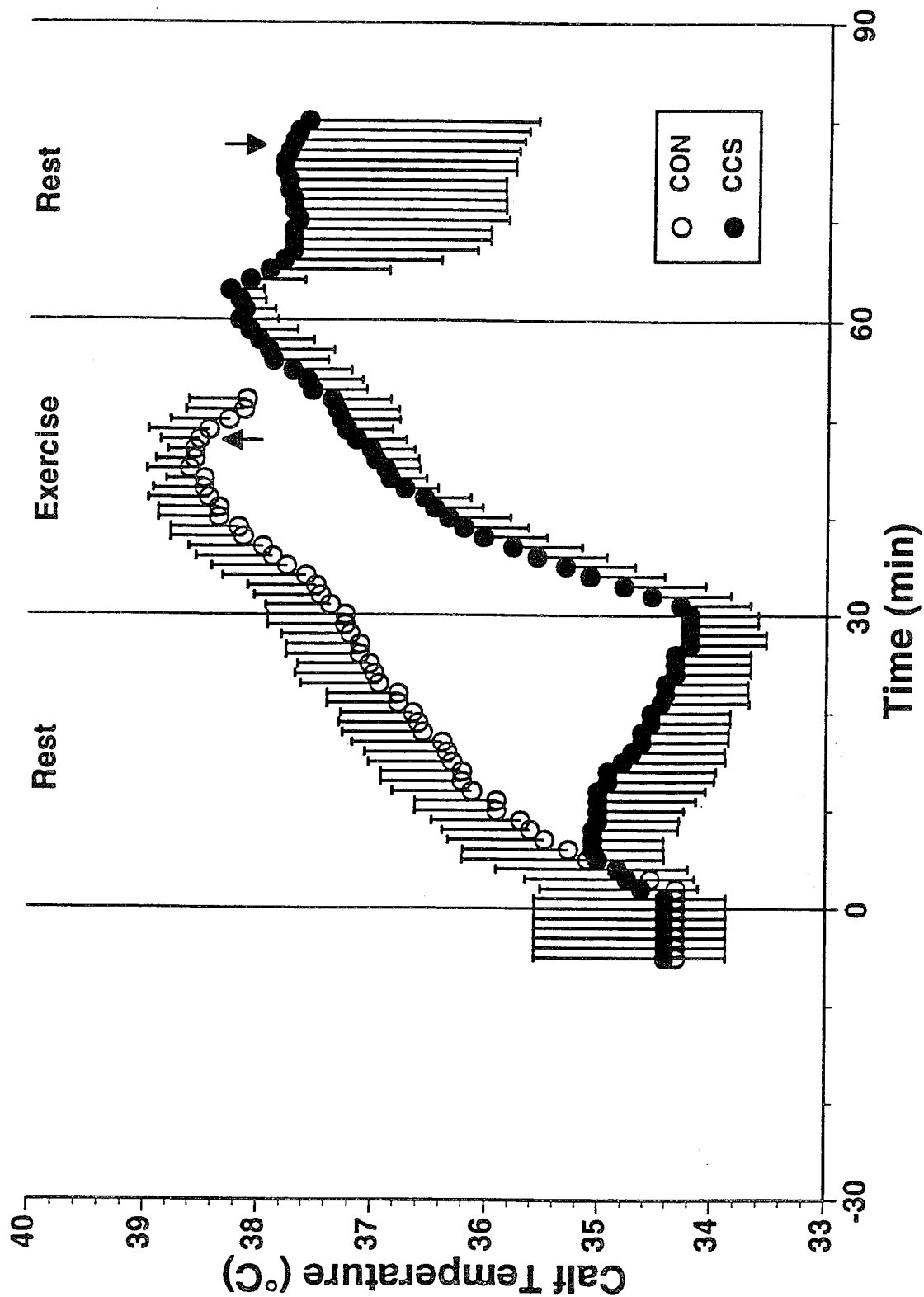
11D

Figure 6. Calf temperature responses for CCS and CON during seated rest and walking exercise in a hot/humid environment. Arrows represent mean end-of-exposure times for CON and CCS.

During the first exercise period, T_{re} increased at a slower rate (p < .05) for CCS than CON. During this time, skin temperatures for CON continued to increase reaching average peak values ranging from 38.7°C to 39.1°C, while all skin temperatures for CCS remained significantly below those of CON. However, as exercise continued, all skin temperatures increased at a greater rate for CCS than for CON (Table 4). The rapid increase in exercise skin temperatures for CCS was partially related to lower temperature values at the end of the first rest period compared to CON.

Table 4.   Slopes of increases in skin temperatures for CON and CCS during the first exercise period.

	T_{ch} (°C•min^{-1})	T_{ua} (°C•min^{-1})	T_{th} (°C•min^{-1})	T_{ca} (°C•min^{-1})
CON	0.05 ± 0.02*	0.05 ± 0.02*	0.07 ± 0.01*	0.11 ± 0.02*
CCS	0.15 ± 0.05	0.11 ± 0.02	0.11 ± 0.04	0.22 ± 0.02

*CCS values significantly higher (p < .05) than CON.

During the first exercise period, T_{re} increased rapidly for CON and CCS with the rate of increase for CCS significantly slower (p < .05) than CON. During this time, skin temperatures for CON continued to increase rapidly, while skin temperatures for CCS, starting at lower values, increased at rates which were significantly greater (p < .05) than CON.

During the second rest period, T_{re} and all skin temperatures for CCS continued to increase. However, despite differences in T_{re}, T_{ch}, T_{ua}, T_{th}, and T_{ca} during the first rest and exercise periods, differences in peak body temperatures between CCS and CON at termination of heat exposure were nonsignificant (Table 5).

Table 5. Comparison of peak body temperatures recorded for CON and CCS at termination from heat exposure.

	T_{re} (° C)	T_{ch} (° C)	T_{ua} (° C)	T_{th} (° C)	T_{ca} (° C)
CON	38.2 ± 0.7	38.7 ± 0.3	38.9 ± 0.5	38.7 ± 0.6	39.1 ± 0.4
CCS	38.5 ± 0.5	38.0 ± 1.5	38.2 ± 1.2	38.5 ± 0.6	38.7 ± 0.5

<u>Ratings of Perceived Exertion and Thermal Sensation.</u>

Analysis of main and interaction effects on RPE and regional TS through minute 45 of heat exposure are shown in Table 6.

Table 6. Analysis of variance for RPE and regional TS.

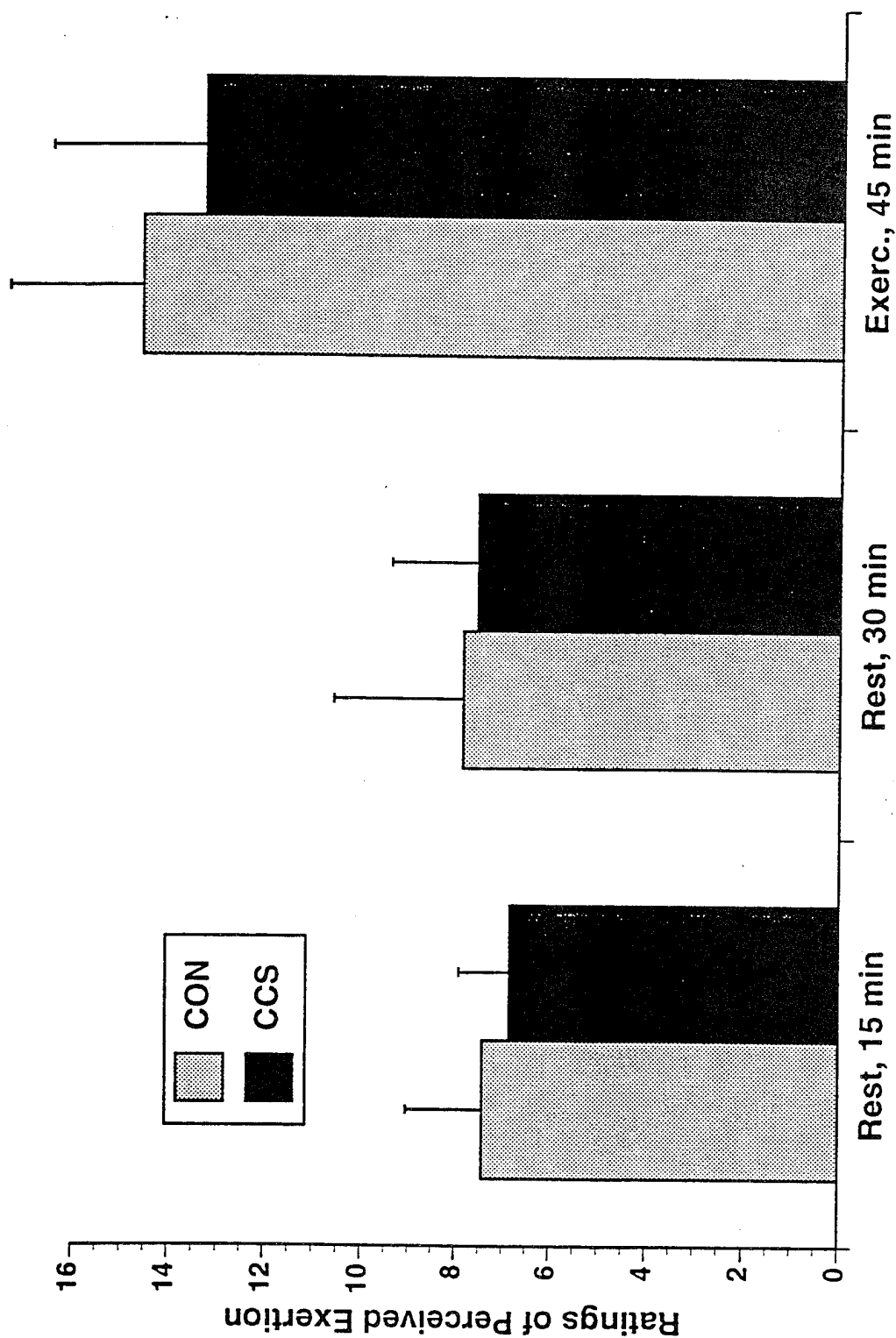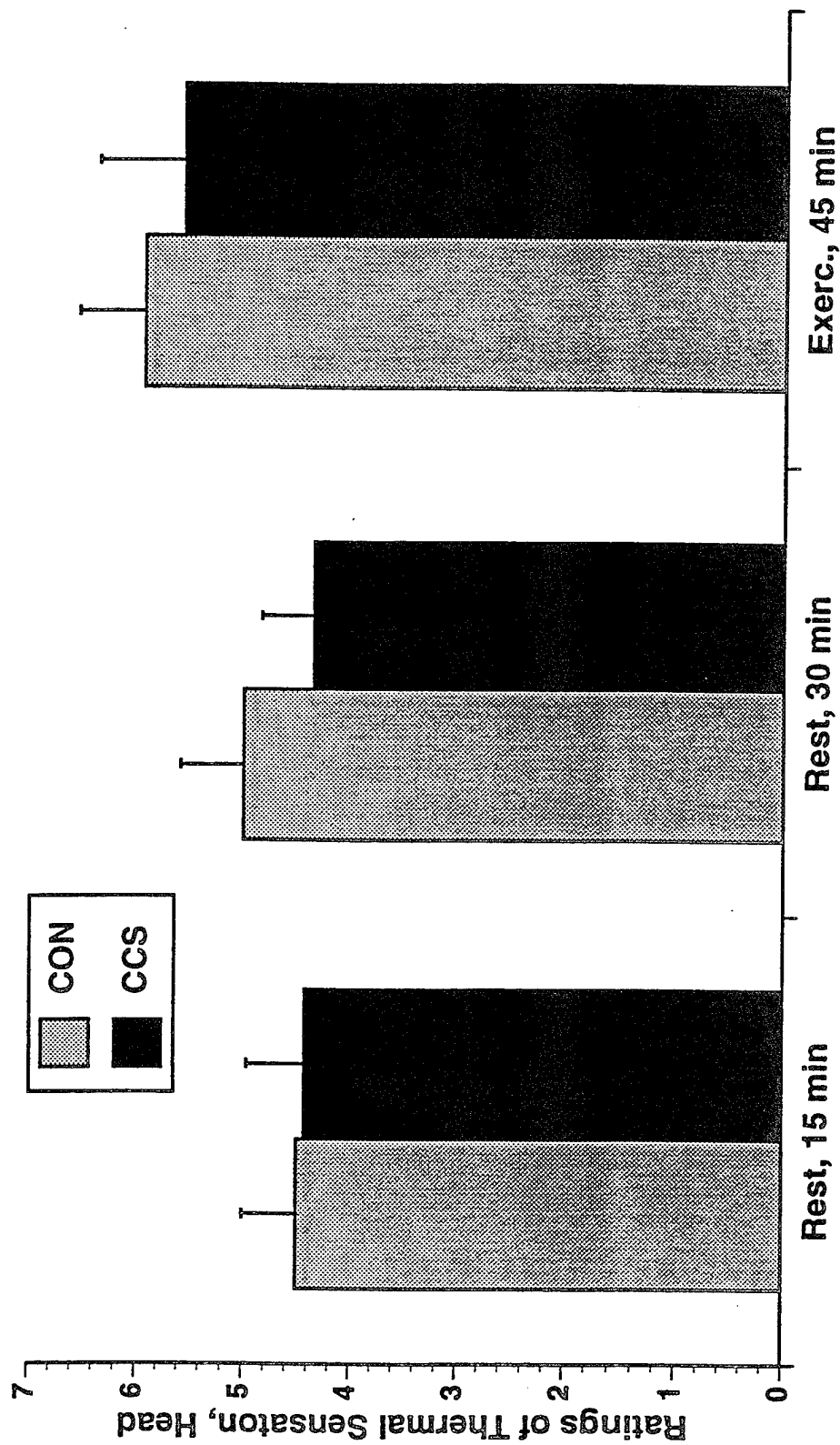| Variable	Time	Trial	Time x Trial
RPE	$p < .0001$	n.s.	n.s.
head TS	$p < .0001$	n.s.	n.s.
neck TS	$p < .0001$	n.s.	n.s.
chest TS	$p < .0001$	$p < .0014$	n.s.
arms TS	$p < .0001$	n.s.	n.s.
legs TS	$p < .0001$	n.s.	n.s.

Figure 7. Ratings of perceived exertion for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in RPE between CCS and CON were nonsignificant.

Figure 8. Ratings of chest thermal sensation for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in TS between CCS and CON were nonsignificant.
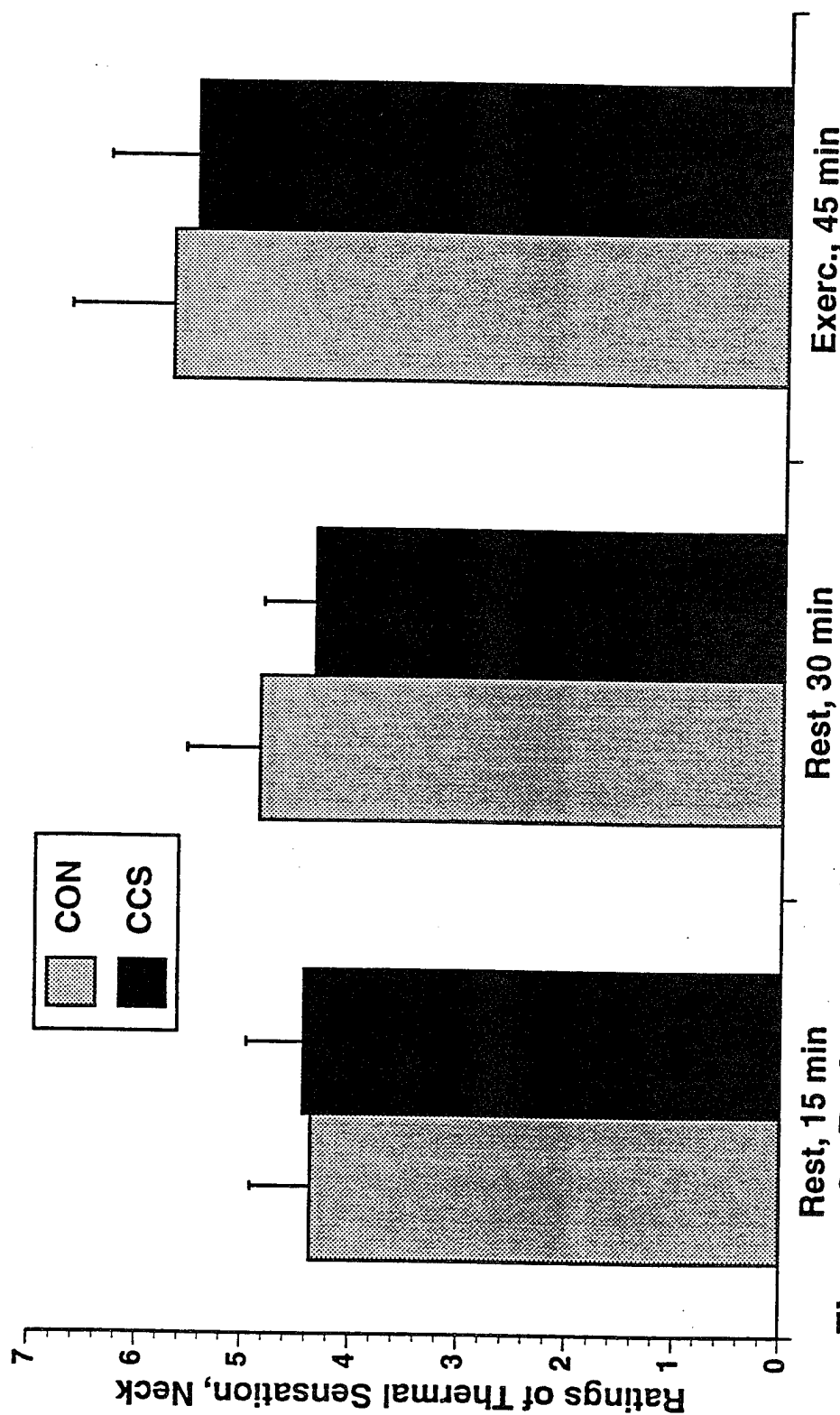
Figure 9. Ratings of neck thermal sensation for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in TS between CCS and CON were nonsignificant.
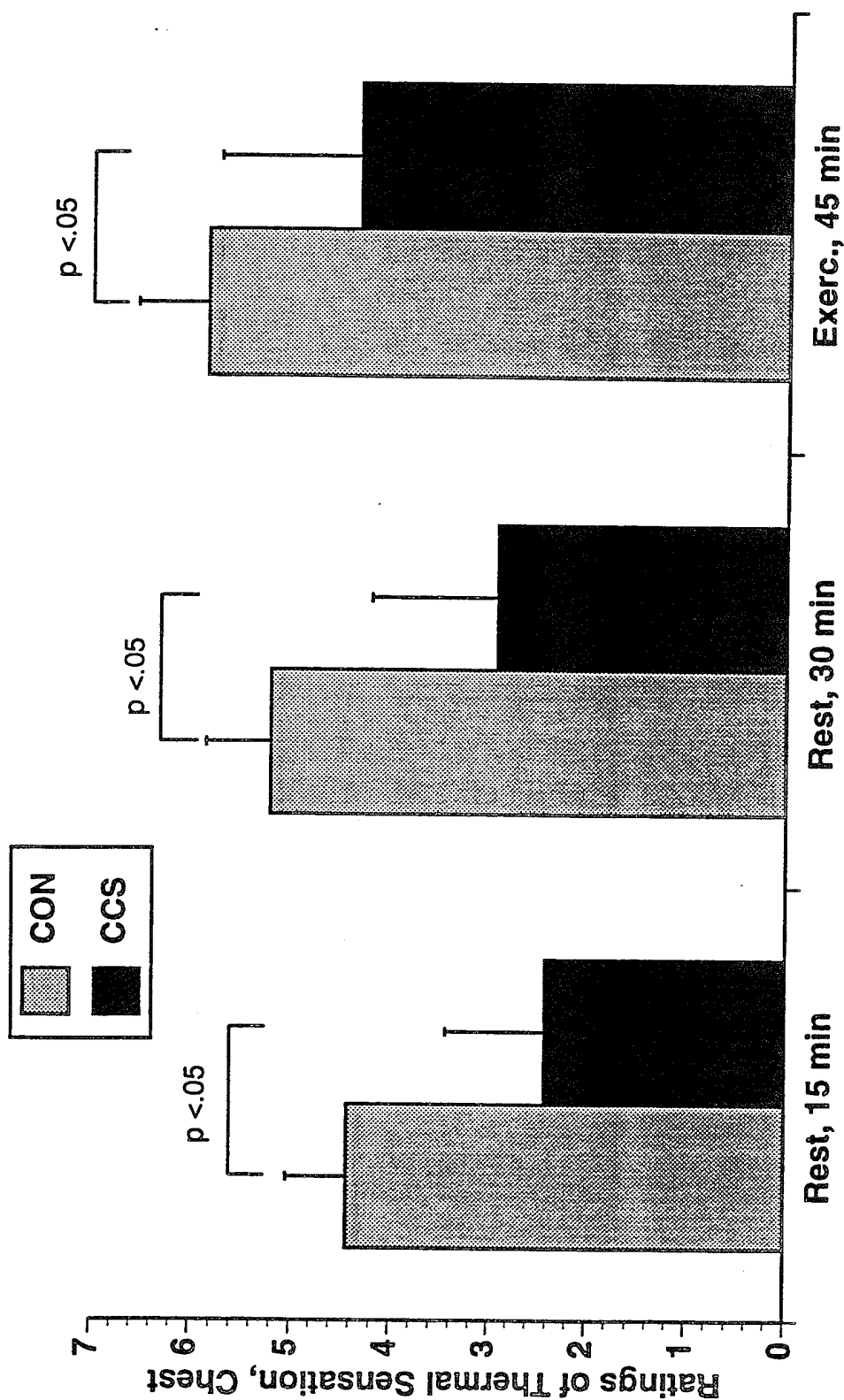
13C

Figure 10. Ratings of chest thermal sensation for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in TS between CCS and CON for rest and exercise were significant (p<0.05).

13D
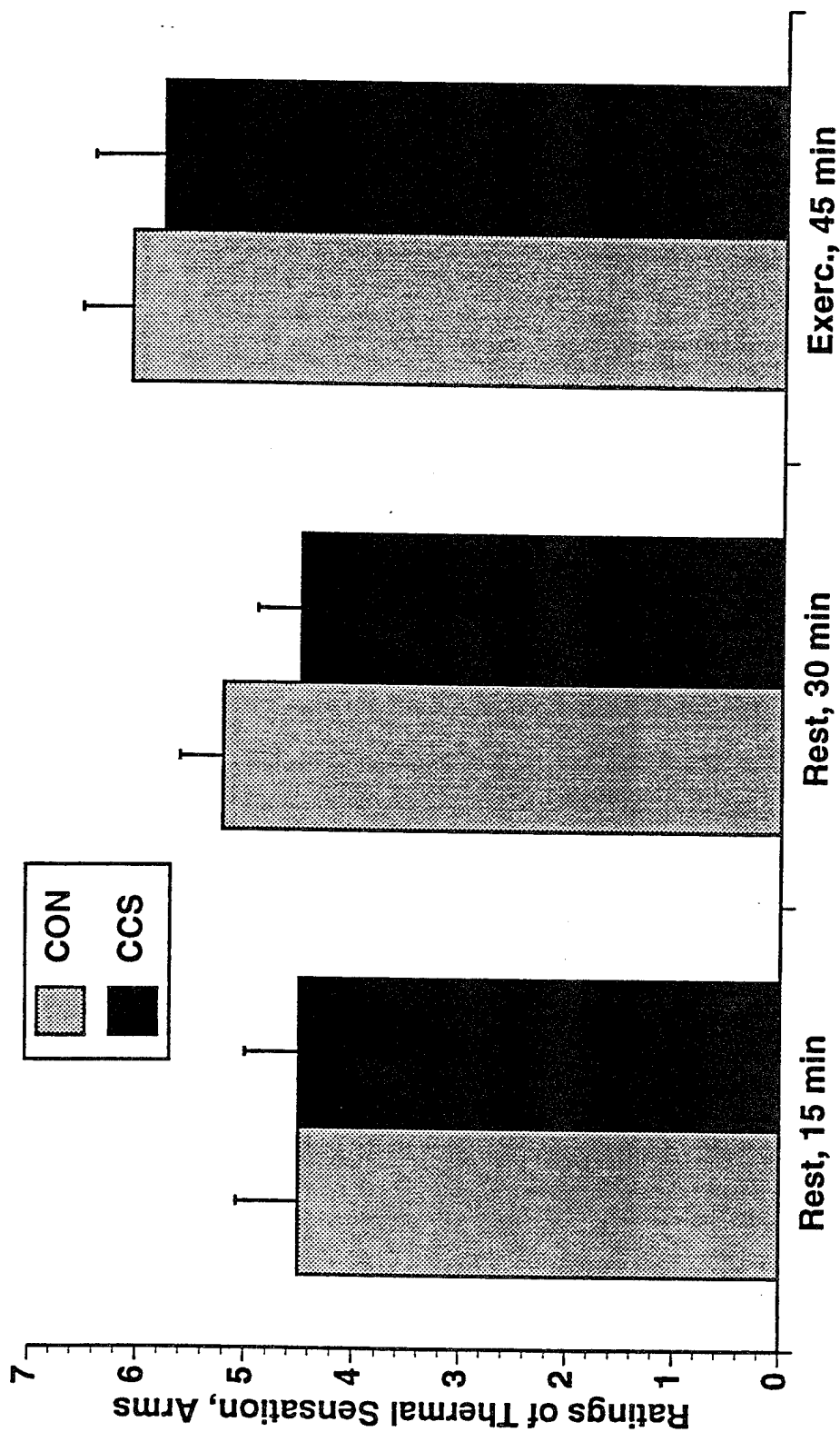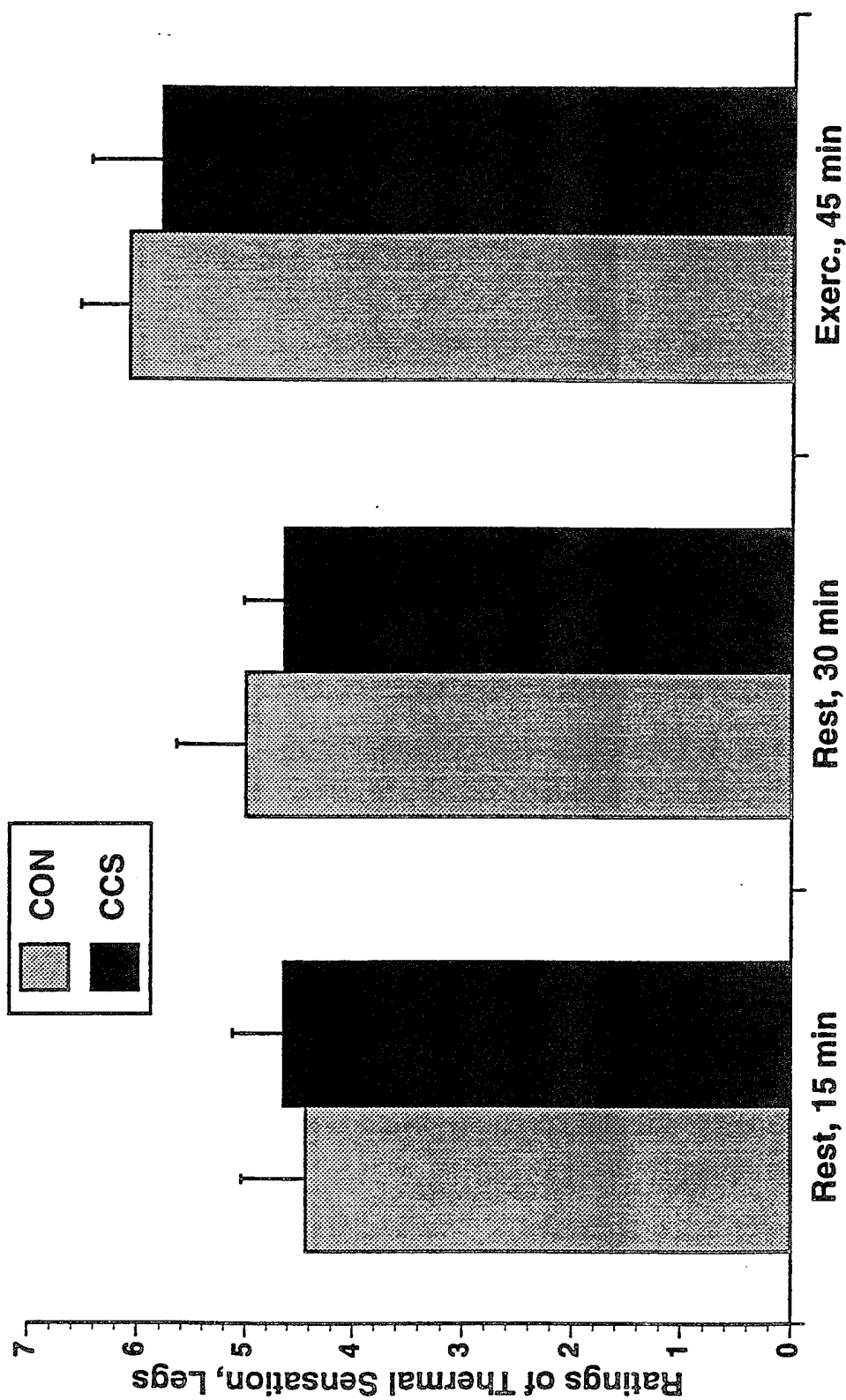
Figure 11. Ratings of arms thermal sensation for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in TS between CCS and CON were nonsignificant.

Figure 12. Ratings of legs thermal sensation for CCS (n = 7) and CON (n = 7) during the first rest and exercise periods. Differences in TS between CCS and CON were nonsignificant.

Differences in average resting RPE between CCS (7.2 ± 1.4) and CON (7.6 ± 2.2) recorded during the first rest period were nonsignificant (Table 6). During the first exercise period, RPE increased with increases in HR and energy expenditure (Fig. 7), however, differences in RPE for CCS (13.3 ± 3.1) and CON (14.6 ± 2.8) were nonsignificant.

All regional TS values increased significantly during the first 45 min of rest and exercise. Regional TS values tended to be lower for CCS and CON, however, the differences for the head (Fig. 8), neck (Fig. 9), arms (Fig. 11), and legs (Fig. 12) were nonsignificant (Table 6). Regional TS for the chest was significantly lower for CCS compared to CON (Fig. 10).

DISCUSSION

The purpose of this study was to evaluate the effectiveness of CCS and portable HEU to minimize heat strain in men dressed in the U.S. Navy FFE and OBA while resting and exercising in a hot/humid environment. We hypothesized that CCS would reduce heat strain and extend heat exposure stay time. The findings support our hypothesis.

Effect of CCS on Exposure Stay Time and Energy Expenditure.

Heat exposure stay times were significantly longer for CCS compared to CON. This occurred as a result of rapid attainment of medical criteria for termination from heat exposure for CON, and lower T_{re} and skin temperature responses for CCS. The greater stay time for CCS supports the findings of Bernard et al. (1992) for subjects wearing the same CCS and portable HEU and exercising in WBGT of 32°C.

In our study, subjects wearing CCS and the portable HEU carried a total weight of 24 kg, while CON subjects carried 18 kg. Despite this weight difference, differences in energy expenditure between CCS and CON were nonsignificant. Interestingly, exercise energy expenditure for both CCS and CON was 22% greater than that predicted for subjects carrying an equivalent amount of weight on the back and walking at the same velocity and grade (Pandolf

et al., 1977). Thus, regardless of whether or not a microclimate cooling system is worn, walking in full FFE is associated with a high level of energy expenditure.

Effect of CCS on Cardiac Responses

For CCS and CON, HR increased slowly during the first rest period and rapidly during the first exercise period. Even though differences in peak HR between CON (end of exposure) and CCS (end of first exercise period) were nonsignificant, CON subjects experienced more terminations from heat exposure as a result of reaching 90% of HR maximum. Early attainment of medical termination criteria for CON subjects is likely due the initial 30 min seated rest period and its impact on cardiovascular function. Rest and exercise in hot environments leads to splanchnic and renal vascular vasoconstriction, a decrease in central blood volume, and rapid increase in HR and Q_c in order to support both active muscle blood flow and redistribution of blood to the skin to support heat dissipation (Rowell, 1983). Support for this explanation comes from the exercise Q_c of CON and CCS which averaged 13.1 L·min·$^{-1}$ This value is higher than the expected 10.5 L·min^{-1} value for exercise of a similar energy expenditure conducted in a thermoneutral environment (Nadel et al., 1979). Although differences in HR, Q_c, and SV during rest and exercise between CCS and CON were nonsignificant, CCS reduced the number terminations from heat-exposure due to elevated HR, and subsequently, contributed to a significant increase in heat exposure stay time.

Effect of CCS on Body Temperatures.

The CCS used in this study reduced the onset and rate of development of heat strain and increased stay time. In a previous study comparing the same CCS to other cooling systems, Bernard et al. (1992) reported lower T_{re} and HR values and extended performance time for subjects exercising in a warm environment. However, in the Bernard et al. (1992) study, the ice-container was replaced whenever water in the container reached 10°C. In our current study, we used only one ice-filled container per test. Periodic replacement of the container may have provide a greater cooling capacity of CCS and even longer stay times.

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During the first rest period, CCS were able to maintain thermal balance, while CON by the end of the first rest period were gaining heat. During the first exercise period, CON continued to gain heat until the end of heat exposure. During this period, CCS also gained heat, but at a slower rate. For CCS, the lower skin temperatures during the first rest period, and lower rate of increase in T_{re} and delayed rise in skin temperatures during the first exercise period were due to heat exchange promoted by the HEU. However, the rapid increases in skin temperatures during the first exercise period experienced by CCS subjects suggests that the rate of heat dissipation provided by the HEU was incapable of removing gains in body heat coming from energy expenditure and heat exposure. Thus, during the first exercise period, CCS was unable to equal the rate of heat production from exercise and heat gain from the environment. This suggests that WCTS and portable HEU systems providing a set liquid flow rate may be of limited value during moderate levels of energy expenditure and exposure to high heat and humidity.

Effect of CCS on RPE and TS.

In the present study, differences in RPE between CON and CCS were nonsignificant. This finding is contrary to that reported by Bennett et al. (1993b) for exercise of the same intensity in a warm/humid environment, but similar to that of Potteiger and Weber (1994) for exercise in a warm environment, and Hagan et al. (1994) and Ramirez et al. (1995) for exercise in a hot/humid environment. Thus, our findings suggest that RPE is unaffected by CCS during exercise in a hot/humid environment, and that RPE is dependent upon energy expenditure.

Our results also suggest that body cooling had no effect on the relationship between RPE and HR. In the RPE scale developed by Borg (1982), RPE values range from 6 to 20 to correspond to HR values of 60 to 200 bt•min^{-1}. During seated rest, HR for CON and CCS ranged from 80 to 110 bpm, while RPE corresponded to "very light." During exercise at an energy expenditure of 400 W, HR for CCS increased to 145 bpm and RPE increased to 13 or "somewhat hard," while HR and RPE for CON increased to 160 bpm and 14.6 or "hard," respectively. These RPE values are similar to what would be expected for exercise in a thermoneutral environment. Thus, our findings suggest that RPE-HR relationship is essentially maintained for rest and exercise in a hot/humid environment.

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Normally, the perceptions of TS parallel skin temperature (Gagge et al., 1967). In the present study, all TS values increased with exercise and heat exposure in accordance with the increases in T_{re} and all skin temperatures. The significantly lower chest TS value for CCS compared to CON is a reflection of the lower chest skin temperature as a result of wearing CCS. However, it is surprising that differences in head, neck, arm, and leg regional TS responses were nonsignificant between CCS and CON when all skin temperatures were lower for CCS. Thus, it appears that main effect of CCS on regional TS values is confined solely to the chest region where CV has the greatest and closest contact with the skin.

Application of CCS and Portable HEU to Shipboard Firefighting.

In this study, use of CCS and portable HEU minimized heat strain and increased heat-exposure stay time. However, this CCS and HEU may not be useful for shipboard firefighting. Use of CCS required the undergarment containing the tubing network to be directly against the skin. Allowing naval personnel time to dress in CCS would increase the response time to active firefighting. Also, we found that the OBA straps rubbed on the tubing network covering the shoulders causing discomfort to the subjects. This discomfort was also present when the hard helmet was worn over the tubing network of the head hood. Another problem with regard to the tubing network involved the distribution and spacing of tubing within the cotton undergarment. The heat dissipation capacity of CCS could likely be improved if the tubing network design conformed to the recommendations of Shvartz (1972). In addition, use of the portable HEU required the unit to be worn outside of the FFE and to one side of the body. This made it difficult for the subjects to walk on the treadmill. This necessity would surely hinder firefighting activities. Lastly, the HEU required an ice-filled plastic container for operation. Providing a continuous supply of frozen containers to individual team members could be a logistical problem during firefighting operations.

SUMMARY

CCS worn under dungarees and the FFE significantly prolonged stay time during rest and exercise in a hot/humid environment of 48°C and 50% rh. CCS also was associated with lower

T_{re} and skin temperatures. However, this CCS may not be useful as a countermeasure to heat strain associated with shipboard firefighting. We found that: 1) the OBA straps rubbed on the CCS tubing network covering the shoulders causing discomfort to the subjects, 2) the necessity of wearing the HEU outside of the FFE and to one side of the body made if difficult for the subjects to move and walk on the treadmill, 3) the HEU possessed a limited capacity to dissipate body heat. Nevertheless, our findings showed that CCS minimized heat strain which led to an increase in stay time.

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13. ABSTRACT (Maximum 200 words)

Firefighting in the Navy firefighting ensemble (FFE) prevents heat dissipation while exposure to high temperatures leads to progressive heat gain. Previous studies in air up to 35°C show that the Core-Control™ system (CCS) with portable heat exchanger reduce heat strain. However, the ability of this system to reduce heat strain in individuals wearing FFE during exposure to hot/humid air is unknown. The purpose of this study was to evaluate CCS to minimize heat strain in men dressed in the Navy FFE, while resting and exercising in hot/humid air (48°C/118°F, 50% rh). Seven males attempted to complete as many cycles as possible of 30 min rest and 30 min walking during two trials (no vest[NV] & CCS). Measurements included rectal (T_{re}) and four skin temperatures, and heart rate. Stay time for CCS (76.6±10.9 min) was longer (p<.05) than NV (49.0±6.6 min). Use of CCS produced significantly lower T_{re} and skin temperatures during both rest and exercise. Our findings indicate that CCS worn under the firefighting ensemble attenuates increases in body temperatures and prolongs heat exposure stay time in a hot/humid environment.

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